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HIGH-FLUX TRIPLE BED CIRCULATING FLUIDIZED BED (TBCFB) GASIFIER FOR EXERGY RECUPERATIVE IGCC/IGFC

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Abstract

The flow behavior of silica sand, of average particle size 128 μm, was investigated using a large-scale triple-bed combined circulating fluidized bed (TBCFB) cold model, which was composed of a 0.1 m I.D. ×16.6 m tall riser, a solids distributor, a 0.1m I.D. × 6.5 m long downer, a gas-solids separator, a 0.75 m × 0.27 m × 3.4 m bubbling fluidized bed and a 0.158 m I.D. × 5.0 m tall gas-sealing bed (GSB) with a high solids mass flux. The main focus of this study is to determine effect of riser secondary air injection on solids mass flux (G_s) and solid holdup. G_s slightly increased by secondary air injection when the riser gas velocity (U_{gr}) was less than 10 m/s. This was caused by the increase in the pressure difference between the GSB and the riser. Secondary air injection had little influence on the solid holdup in the riser. The mixing between silica sand and coal particles was investigated for two different coal feeding arrangements by coupling Computational Fluid Dynamics (CFD) with the Discrete Element Method (DEM). The results show a tangential arrangement provided better mixing than a normal arrangement except near the entrance.

INTRODUCTION

Coal utilization is one of the major contributors of anthropogenic CO_2 and pollutants emission. Clean Coal Technology (CCT) has been under development to find ways for more efficient utilization of coal. So far, Integrated coal Gasification Combined Cycle (IGCC) and Integrated coal Gasification Fuel-cell Combined cycle (IGFC) have been developed to increase the thermal efficiency of coal-fired power plants.

For improvement of the thermal efficiency of coal-fired IGCC/IGFC, an advanced IGCC (A-IGCC) or advanced IGFC (A-IGFC) system with exergy recuperation was proposed (1,2). In this system, the waste heat from a gas turbine or solid oxide fuel cell is recuperated as a heat source for steam gasification of coal to reduce the partial combustion of coal. Because the reaction temperature for gasification is expected to be 700-900 °C, which is not suitable for conventional entrained bed gasifiers, a novel triple-bed combined circulating fluidized bed (TBCFB) gasifier was proposed (3-5). The TBCFB is composed of a downer pyrolyzer, a bubbling fluidized bed (BFB) char gasifier, and a riser partial combustor of unreacted char. The heat generated in the riser partial combustor is supplied to the downer pyrolyzer for the endothermic reaction by using a heat media such as silica sand (3-5). According to the mass and energy balance calculation for the system (2,6), the solids mass flux (G_s) of the heat media should be 511 to 684 kg/(m^2•s), which is much higher than in a conventional CFB (7-10) to make the A-IGCC/IGFC system feasible.

Besides the requirement for a high solids flux of the heat media, the mixing behavior between the heat media and reactant, i.e. silica sand and coal, is also critical. Since the residence time of the solid particles in the downer is usually quite short, the heat carried by the silica sand needs to be effectively transferred to the coal for pyrolysis. In this study, a preliminary investigation was carried out to study the mixing behavior between sand and coal particles by numerical simulation.

In our previous study (5), we set up a large-scale TBCFB gasifier cold model and investigated flow behavior of the sand particles. The maximum obtained G_s was over 400 kg/(m^2•s) when the riser gas velocity (U_{gr}) was 12 m/s, and the average solid holdup in the bottom dense region of 0.110 to 0.122 at G_s=377 to 410 kg/(m^2•s) was achieved by installing a gas-sealing bed (GSB) between the riser and BFB. However, it was observed that some amount of air passed from the riser bottom to the GSB bottom when the riser gas velocity was high. Thus, in this study, some amount of riser gas was injected in the second nozzle 1.9 m above the riser bottom and the influence of the secondary air on G_s and solids holdup was investigated.

EXPERIMENT AND SIMULATION

Experimental

Figure 1 shows a schematic image of the large scale TBCFB cold model, which is composed of a riser (0.1 m I.D. × 16.6 m), a solid distributor for downer, a downer (0.1 m I.D. × 6.5 m), a gas-solid separator and a BFB (0.75 × 0.27 × 3.4 m^3). Sand particles with a density of 2600 kg/m^3 and an arithmetic average particle size of 128 μm (minimum fluidization velocity was 0.0074 m/s) were used as bed material. To increase the driving force to transport a large amount of particles from the BFB into the riser bottom, a gas-sealing solids bed (0.158 m I.D. × 5.0 m) was installed. The sand particles overflowed from the BFB were transported to the GSB through an inclined tube. The sand particles were fluidized by air in the GSB and transported to the riser bottom. The bed height in the GSB was 4.0 m. At the top of the riser, the solids passed through a smooth elbow into cyclone 1 for gas-solids separation, and some small solids were collected by cyclones 2 and 3, and returned to the dipleg of cyclone 1. At the top of the downer, the solids were redistributed by a solids distributor with 13 vertically positioned brass tubes with a diameter of 19 mm using an air assist. The air was introduced into the downer at the entrance of the downer and the solids and air flowed downwardly. At the end of the downer, the solids were separated from the air by a separator and passed to the BFB. The solids entrained by the gas were collected by a cyclone and returned to the BFB. For the seal between the downer and the BFB, a seal tube (0.15 m I.D. × 1.0 m long) was inserted into the BFB. In this study, the superficial gas velocity of the riser was changed in two ways: i) the air was fed from the bottom of the riser at a volumetric rate to give 6 to 12 m/s in the riser without secondary air injection, ii) the air fed from the bottom of the riser was fixed at volumetric rate to give 6 m/s in the riser and secondary air was fed at the nozzles located 1.9 m above the riser bottom at a volumetric rate to give 0 to 6 m/s in the riser. The superficial gas velocity in the GSB and BFB were fixed at 0.10 and 0.025 m/s, respectively. Static

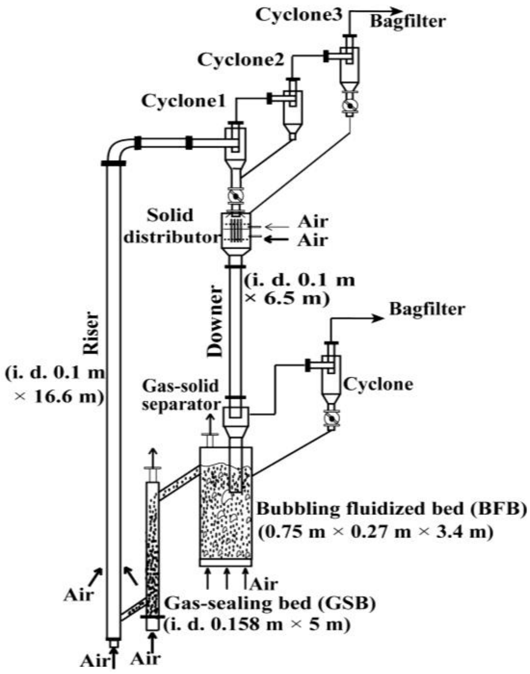
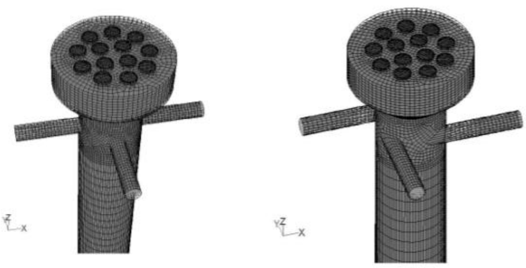


Figure 1 Experimental apparatus (5)

pressures were measured at 47 pressure taps around the unit using differential pressure sensors (Keyence Corp., AP48). The output signals from the sensors were acquired at a sampling frequency of 100 Hz via a data logger (CONTEC, AIO-163202FX) and a laptop computer. Solids mass flux (G_s) was measured by closing a butterfly valve below the cyclone 1 and measuring the time to accumulate given amounts of particles. This was determined from the mean value after 10 measurements at a steady state.

Simulation

The commercially available CFD code FLUENT (Ansys, Inc) and a Discrete Element Method (DEM) based code EDEM (DEM-Solutions Ltd) were used to study the dynamics of coal and sand particles in the downer. The air flow was solved by FLUENT using an Eulerian approach, and particle motion was computed by EDEM using a Lagrangian approach. At every time step the two methods were coupled such that interactions between gas and solid particles were handled rigorously. Due to CPU and memory limitations, simulations were carried out for sand particles 4 mm in diameter and coal particles 6 mm in diameter in a downer of 2 m in length. The other geometrical dimensions were the same as those in the experimental setup.



(a) Normal (b) Tangential

Figure 2 Arrangements of 4 nozzles for coal feeding

The basic equations for air flow in the downer are the continuity and momentum equations (11)

$$\frac{\partial(\varepsilon\rho)}{\partial t} + \nabla\cdot(\rho\varepsilon\vec{u}) = 0 \quad (1)$$

$$\frac{\partial(\varepsilon\rho\vec{u})}{\partial t} + \nabla\cdot(\rho\varepsilon\vec{u}\vec{u}) = -\nabla p + \mu\varepsilon\nabla^2\vec{u} + \rho\varepsilon\vec{g} - \vec{S} \quad (2)$$

where ε is the air volume fraction, $\vec{g}$ is the gravity force vector, $\vec{S}$ is the momentum sink and the coupling between the gas and solid phases is achieved through the calculation of the momentum sink of the drag force that arises due to the slip velocity between the phases. The momentum sink $\vec{S}$ is calculated by: $\vec{S} = \frac{\sum \vec{F}_D}{V}$, where

V is the volume of a CFD mesh cell, and $\vec{F}_D$ is the summation of the drag force exerted on the fluid in the mesh cell. The free stream drag model adopted was

$$\vec{F}_D = 0.5 C_D \rho A |\vec{v}| \vec{v} \tag{3}$$

where the drag coefficient C_D depends on the Reynolds number (11)

$$\mathrm{Re_p} = \frac{\varepsilon \rho d_\mathrm{p} v_r}{\mu} \tag{4}$$

$$C_D = \begin{cases} \dfrac{24}{\mathrm{Re_p}} & \mathrm{Re_p} \le 0.5 \\ 24\left(1.0 + 0.15\,\mathrm{Re}_p^{0.687}\right)/\,\mathrm{Re_p} & 0.5 < \mathrm{Re_p} \le 1000 \\ 0.44 & \mathrm{Re_p} > 1000 \end{cases} \tag{5}$$

The sand particles were fed into the downer through 13 tubes in the distributor, and two nozzle arrangements were designed to feed coal into the downer, as shown in Fig.2. The four feeding nozzles were all horizontal. One arrangement was that all the four nozzles were normal to the downer, and the other arrangement was that all four nozzles were tangential to the downer. The uniform inlet velocity for the nozzle was 20 m/s, the standard $k \sim \varepsilon$ turbulent model was adopted.

RESULTS AND DISCUSSION

Effect of secondary air injection on G_s

Figures 3 and 4 show the solids mass flux (G_s) and the pressure difference between the GSB and riser bottom as a function of riser gas velocity (U_{gr}), respectively. Note that U_{gr} was defined as the sum of air fed from the riser bottom and the secondary injection nozzle divided by the cross section of the riser. When no secondary air was injected, G_s monotonically increased with the increase in U_{gr}. The maximum G_s obtained was 433 kg/(m^2•s) at U_{gr} =12 m/s. When secondary air was injected, G_s peaked at 451 kg/(m^2•s) at U_{gr} =10 m/s (i.e. 6 m/s was fed from the bottom and 4 m/s was fed from the nozzle). Further increases

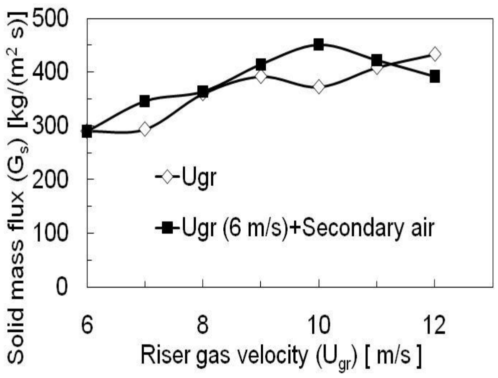


Figure 3 Relationship between riser gas velocity (U_{gr}) and solid mass flux (G_s)

in U_{gr} decreased G_s. Compared with the results without secondary air injection, the G_s was slightly larger at $U_{gr} \leq 10$ m/s. However, the influence of secondary air injection was not significant at velocities $U_{gr} \geq 11$ m/s. It can be seen in Figure 4 the pressure difference between the GSB and riser bottom, which is a major driving force to transport solids to riser, became larger when secondary air injection was used. Thus, it can be said secondary air injection is an effective way to increase G_s when the total U_{gr} is not high.

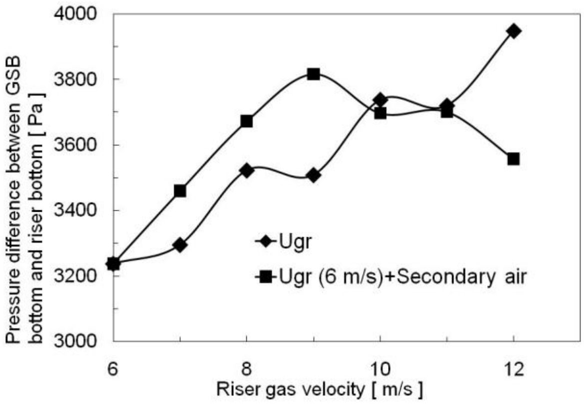


Figure 4 Relationship between riser gas velocity and pressure difference between GSB bottom and riser bottom

Effect of secondary air injection on solids holdup along riser

The influence of secondary air injection on riser solids holdup was also studied. Figure 5 shows the apparent solids holdups (ε_s) along riser calculated by the following equation;

$$\Delta P/\Delta H=\rho_p \varepsilon_s g \qquad (6)$$

where ΔP [Pa], ΔH [m], ρ_p [kg/m^3], ε_s [-] and g [m/s^2] mean pressure difference, the distance between the two sensors, particle density, solids holdup and the gravitational acceleration, respectively. The open and closed symbols represent the results with and without secondary air injection, respectively. ε_s decreased sharply at the bottom part of the riser (Hr < 5 m) and gradually decreased at the middle and top of the riser ($H_r \geq 5$ m). The solids holdup decreased in the riser as U_{gr} increased. When U_{gr} was 10-12 m/s, the ε_s was almost constant (around 0.02) at $H_r \geq 5$ m. The results indicate the formation of dense phase at $H_r < 5$ m and lean phase at $H_r \geq 5$ m. By comparing the results with and without secondary air injection at each U_{gr}, a slight increase in ε_s was observed at bottom dense part ($H_r < 5$ m). However, no significant difference of ε_s

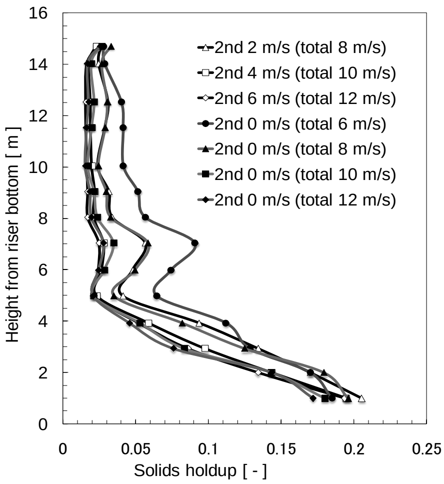
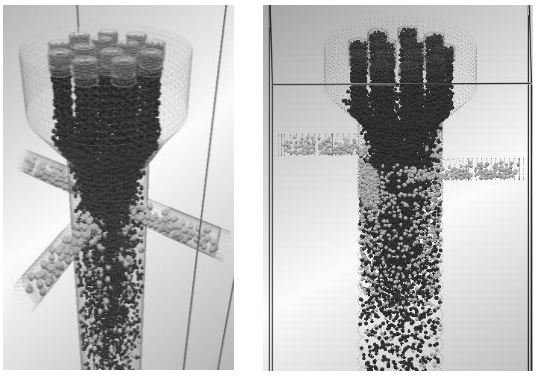


Figure 5 Solids holdup along riser

was observed at middle and top part (H_r ≥ 5 m). This indicated that secondary air injection did not significantly increase solids holdup along riser.

Simulation results

Figure 6 shows the mixing behavior between sand particles (dark) and coal particles (light). It can be seen that near the entrance, the tangential arrangement resulted in a poorer mixing performance than the normal arrangement. This is because in the normal arrangement, strong collisions between the normally injected coal particles and the falling sand particles occurred. In contrast, in the tangential arrangement, the coal particles had a tendency to move spirally along the walls of the downer while most of the sand particles moved downwards along the center of downer. This resulted in less mixing between the coal and sand particles in the latter case. But downstream, the sand and coal particles are distributed more uniformly in the radial direction when the tangential arrangement was used than when the normal arrangement was used, which means the tangential arrangement gave better mixing than the normal arrangement downstream of the feeder.



(a) Normal (b) Tangential

Figure 6 Mixing behaviors for the two types of nozzle arrangements

The mixing of coal and sand particles depends on several parameters, such as particle diameters, inlet velocity, downer diameter and solids mass flux. A sensitivity analysis of these parameters on the mixing is still under study. Also, the mixing content will be quantified and a suitable mixing index will be developed.

CONCLUSIONS

1) Secondary air injection slightly increases solid mass flux (G_s) at a riser gas velocity ≤ 9 m/s. This is thought to due to the increase in the pressure difference between the GSB and the riser bottom, which is the main driving force to transport solids.
2) The injection of secondary air does not affect solids holdup along riser.
3) The tangential arrangement of nozzles for feeding coal particles into the downer provided better mixing between coal and sand particles except near the entrance.

ACKNOWLEDGEMENT

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